SMART Approaches for System-wide Restoration – H&H Connections

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Abstract

One of the strategic research initiatives designed to support the Environmental Operating Principles and sustainable water resource management goals of the Corps of Engineers is the System-wide Modeling, Assessment, and Restoration Technologies (SMART) Program. The objectives of the SMART Program include the development of innovative approaches for predicting biological responses to restoration efforts that often include changes in hydrologic conditions (e.g., reservoir operations). These approaches need to be based on sound science and have reasonable expectations for implementation by field personnel and their partners. Currently, these approaches include the application of existing tools and techniques, customized for specific purposes. For example, a modeling system using a watershed model (e.g., Hydrologic Simulation Program in Fortran (HSPF)) coupled with a 2-Dimensional Water Quality Model (e.g., CE-QUAL W2) can be used for assessing water quality response and resultant habitat quality changes resulting from various ecosystem restoration alternatives. Another approach is to utilize landscape information from GIS databases in combination with additional quantitative inputs from hydrologic models to prioritize areas in a river (e.g., sandbars and islands) for habitat restoration. Approaches that combine hydrologic modeling capabilities with biological criteria (e.g., HEC's Ecosystem Functions Model (EFM)) can be used to predict biological responses to changes in the flow regime. This paper provides an overview of the SMART program and describes approaches for assessing watersheds and water resources with readily available tools.

Introduction

In response to the Corps' direction to encompass concepts of environmental sustainability into our mission and based on needs identified for future operating capabilities, the System-wide Modeling, Assessment, Restoration and Technologies (SMART) Program was developed. The goal of the SMART program is to develop and implement capabilities to provide timely and continuing forecasts of the impacts of human activities on environmental conditions and to effectively communicate these forecasts to stakeholders and decision makers. The program is designed to meet customer needs in planning, construction, and operation and maintenance elements of the Major Subordinate Commands (MSC) (i.e., Divisions) and Subordinate Commands (SC) (i.e., Districts) as well as other stakeholders and partners in ecosystem management and restoration efforts.

In order to accomplish this goal, a wide variety of tools and approaches must be integrated for multi-objective applications at a variety of spatial (small to large watershed and lotic systems) and temporal (physical, chemical, and ecological) scales. The type of tools that can be used for system-wide assessment of restoration activities vary, including screening level tools, Geographical Information Systems (GIS) tools, various levels of watershed models (i.e., lumped parameter and distributive), habitat assessment techniques and "combined approaches" such as the Hydrogeomorphic (HGM) classification system and Ecological Dynamics Simulation (EDYS) model (Figure 1). One of the objectives of the SMART program is to support the effective application of these tools for sustainable water resource management. The focus of this paper is on the hydrologic connections to ecological modeling as exemplified by applications using the Ecosystem Function Model (EFM) and the use of the Hydrologic Simulation Program in FORTRAN (HSPF) coupled to the 2-dimensional water quality model CE-QUAL-W2.

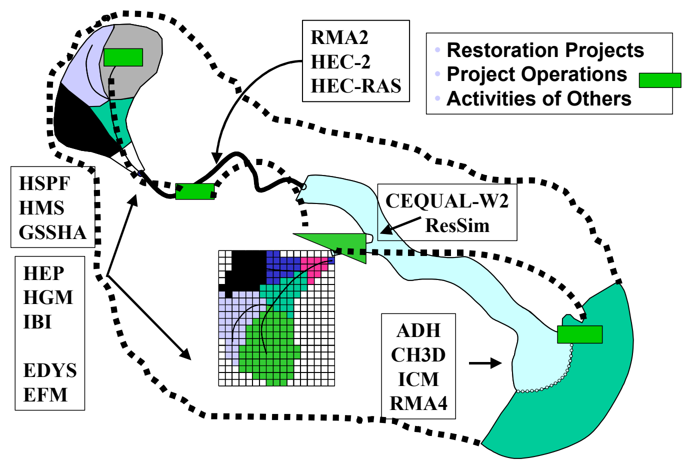

Figure 1. Potential assessment tools for system-wide assessment of restoration activities.

Overview of the SMART Program

The purpose of the SMART research program is to assemble and integrate the varied components of quantitative ecology, to transcend basic research, and to connect and apply current and improved approaches for predicting ecological responses over a variety of scales. The SMART program is built around the general theme of environmental sustainability in Corps planning, engineering, and operations and maintenance of our water resource projects. Principles of landscape and ecosystem ecology, interactions at ecosystem interfaces, techniques for environmental assessment and prediction, adaptive management of resources, restoration and maintenance, economic and social considerations, and science-based decision-making are all underlying components of this theme. Coincidently, user application of SMART products is fundamental to the success of the program and early integration of SMART products with field projects and personnel during product development is essential.

Improved capabilities will lead to more accurate predictions of future environmental conditions affected by the Corps at project and regional (basin/system-wide) scales. These capabilities will be inserted into planning, engineering, and operations and maintenance practices to address diverse environmental issues such as habitat needs for aquatic communities, special requirements of threatened and endangered species, control of nuisance species, water and sediment quality management issues, and accurate prediction of alternative future conditions over a wide range of spatial and temporal scales. Linking environmental assessment tools with sustainability concepts will allow efficient and sound assessment and decision-making for environmental restoration and management. One of the major products of the SMART program will be a web-based framework for system-wide assessments that provides decision-making capabilities for selecting and applying appropriate tools and approaches described above (Figure 2). This framework will support existing, enhanced, and newly developed tools for multi-objective and multi-scale applications.

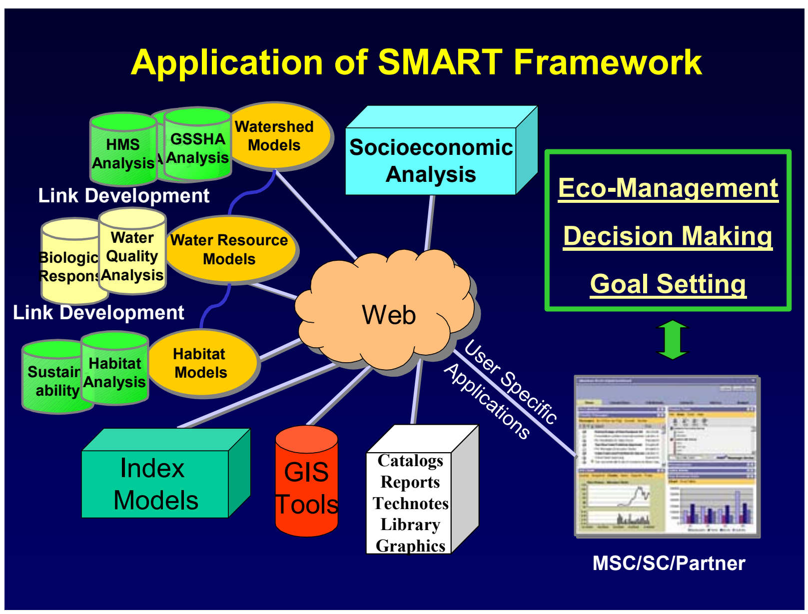

Figure 2. Example of the web-based framework for a system-wide application in SMART.

Overview of the Ecosystem Function Model

The Ecosystem Functions Model (EFM) is a planning tool that analyzes ecosystem response to changes in flow regime. The Hydrologic Engineering Center (CEIWR-HEC), in conjunction with the Sacramento and San Joaquin River Basins Comprehensive Study, has developed the EFM and envisions environmental planners, biologists, and engineers using the model to help determine whether proposed alternatives (e.g., reservoir operations or levee alignments) would maintain, enhance, or diminish ecosystem health.

Central to EFM analyses are "functional relationships." These relationships link characteristics of hydrologic and hydraulic time series (flow and stage) to elements of the ecosystem through combinations of four basic criteria – season, flow frequency, duration, and rate of stage recession. There is no limit to the number or genre of relationships that may be developed and a user interface has been constructed to facilitate entry and inventory of criteria. The pilot application of the EFM used fifteen relationships to investigate a range of ecosystem elements, including fish spawning, fish rearing, fish stranding, recruitment of large woody debris, channel migration, riparian forest regeneration, and many others (Figure 3).

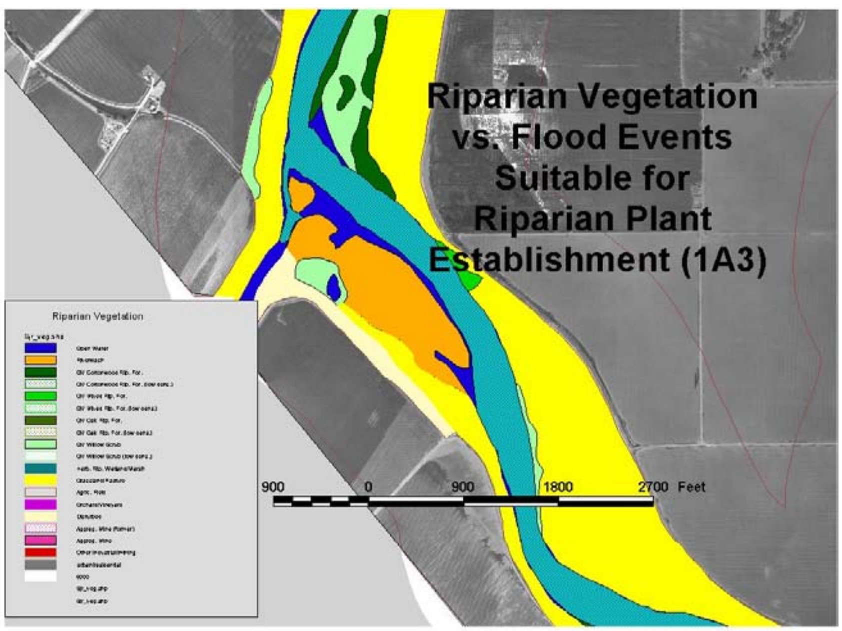

Figure 3. Example graphical output from the EFM depicting potential for riparian zone vegetation types.

After relationships are developed, a statistic computations package (also managed by the interface) analyzes flow and stage time series for the specified criteria and produces a single flow value for each relationship. This process is repeated to assess a modified flow regime and resulting values for without and with project conditions are compared to indicate the direction of change of ecosystem health.

A strength of the EFM is its ability to assess results spatially. In addition to the statistical computations, EFM analyses typically involve hydraulic modeling, which translates statistical results to water surface profiles and spatial coverages of water depth, velocity, and inundated area, GIS capabilities accessed though the EFM display these generated coverages as well as other relevant spatial data (i.e., soils, vegetation, and land-use maps).

Hydraulic modeling and GIS improve EFM applications by helping project teams to visualize existing ecologic conditions and highlight promising restoration sites (see Figure), by computing depth and velocity data that can be used as criteria to further define relationships, and by making it possible to assess multiple alternatives incrementally - through GIS, inundated areas for individual relationships can be compared and ranked as a measure of the relative enhancement (or decline) of that ecosystem element for any number of alternatives.

Overview of the HSPF

The Hydrologic Simulation Program in FORTRAN (HSPF) falls into the category of lumped-parameter models and is generally used to assess effects of land use changes, point or nonpoint source treatment alternatives, flow diversions, and reservoir operations. It is applied to natural and developed watersheds. The model has the capability to simulate land surface and subsurface hydrology and quality (e.g., sediments and nutrient) processes. These simulations can be conducted for multiple pervious and impervious land surfaces within a drainage area. Time steps (divisible by 1) from 1 minute to 1 day can be used and frequency-duration analysis can be done for any time series. The model can also be applied to stream and lake hydraulics and water quality processes (Figure 4).

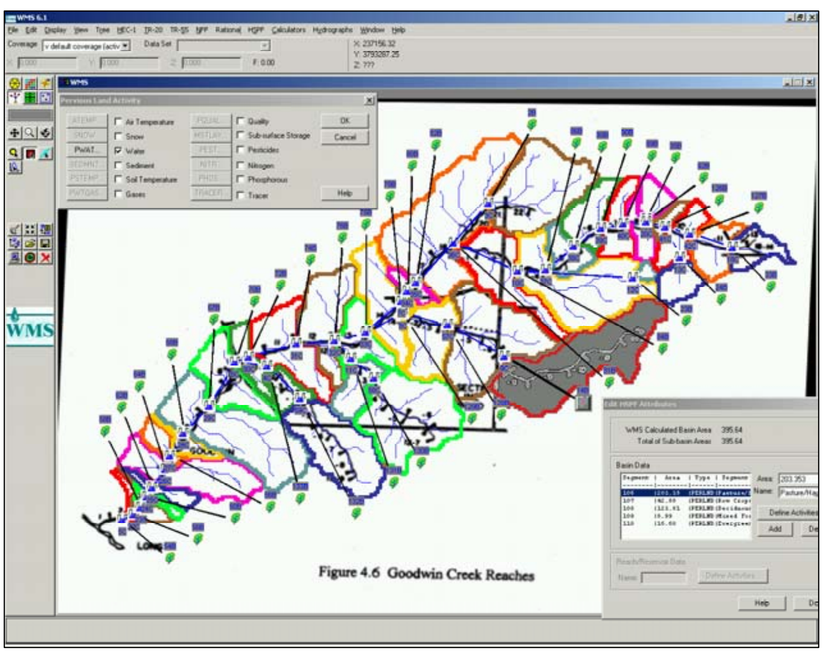

Figure 4. Schematic of stream network and drainages in HSPF.

Streamflow hydrographs are generated with meteorological records, such as continuous rainfall. When hydrographs are combined with water quality data, distribution of pollutants are also generated. Specific capabilities of HSPF include simulation of interception soil moisture, surface runoff, interflow, baseflow, snowpack depth and water content, snowmelt, evapotranspiration, ground-water recharge, dissolved oxygen, biochemical oxygen demand, temperature, pesticides, conservatives, fecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, reservoir routing, constituent routing, pH, ammonia nitrate-nitrite nitrogen, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton, and zooplankton (USGS, url: http://water.usgs.gov/cgi-bin/man_wrdapp?hspf).

Overview of CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional, longitudinal/vertical, hydrodynamic and water quality model and can be run independently or through the CE Watershed Modeling System (Figure 5). Because the model assumes lateral homogeneity, it is best suited for relatively long and narrow waterbodies exhibiting longitudinal and vertical water quality gradients. The model has been applied to rivers, lakes, reservoirs, estuaries, and combinations thereof. The application of CE-QUAL-W2 requires knowledge in the following areas:

1. Hydrodynamics
2. Aquatic biology
3. Aquatic chemistry
4. Numerical methods
5. Computers and FORTRAN coding
6. Statistics
7. Data assembly and reconstruction

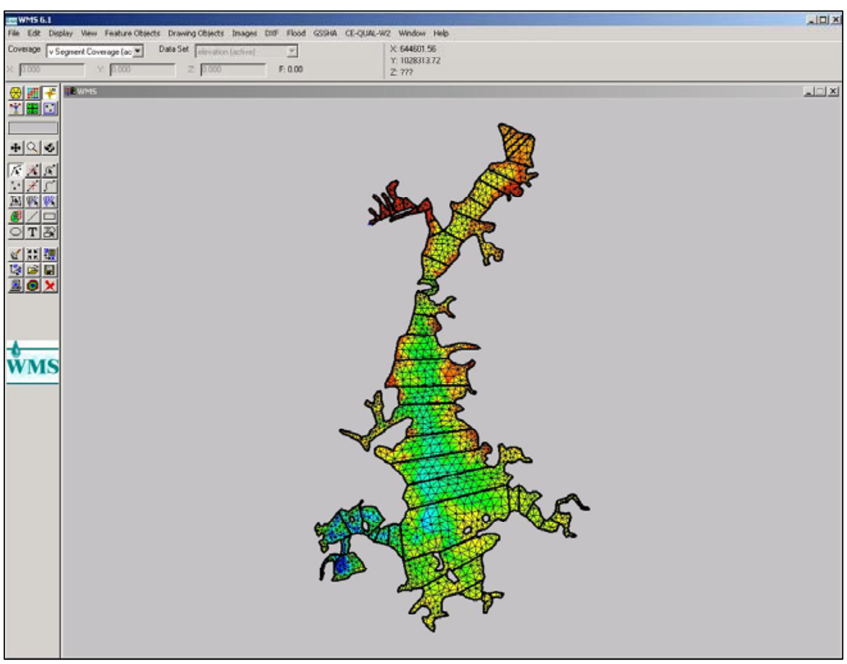

Figure 5. Example of the grid in a CE-QUAL-W2 application.

Capabilities

The model can easily simulate long-term water quality responses. The model can be applied to estuaries, rivers, or portions of a water-body by specifying upstream or downstream head boundary conditions including geometrically complex water-bodies such as dendritic reservirs or estuaries. The model can be applied to any number of rivers, reservoirs, lakes, and estuaries linked in series.

The model predicts hydrodyanimcs of water surface elevations, velocities, and temperatures. Temperature is included in the hydrodynamic calculations because of its effect on water density and cannot be turned off. For water quality, any combination of constituents can be included/excluded from a simulation. The effects of salinity or total dissolved solids/salinity on density and thus hydrodynamics are included only if they are simulated in the water quality module. The water quality algorithm is modular, allowing constituents to be easily added as additional subroutines. Version 3.1 includes the following water quality state variables in addition to temperature:

1. any number of generic constituents defined by a 0 and/or a 1st order decay rate and/or a settling velocity and/or an Arrhenius temperature rate multiplier that can be used to define any number of the following: a. conservative tracer(s), b. water age or hydraulic residence time, c. coliform bacteria(s), or d. contaminant(s)
2. any number of inorganic suspended solids groups
3. any number of phytoplankton groups
4. any number of epiphyton groups
5. any number of CBOD groups
6. ammonium and nitrate-nitrite
7. bioavailable phosphorus (commonly represented by orthophosphate or soluble reactive phosphorus)
8. labile or refractory dissolved or particulate organic matter
9. total inorganic carbon
10. alkalinity
11. total iron
12. dissolved oxygen
13. organic sediments
14. gas entrainment

Additionally, over 60 derived variables including pH, TOC, DOC, TON, TOP, DOP, etc. can be computed internally from the state variables and output for comparison to measured data.

The model includes a variable time-step algorithm that attempts to help ensure stability requirements for the hydrodynamics imposed by the numerical solution scheme are not violated. Provisions are made for inflows and inflow loadings from point/nonpoint sources, branches, and precipitation. The onset, growth, and breakup of ice cover can be calculated as well as the vertical extent of the withdrawal zone based on outlet geometry, outflow, and density.

The model allows the user considerable flexibility in the type and frequency of outputs. Output is available for the screen, hard copy, plotting, and restarts. The user can specify what is output, when during the simulation output is to begin, and the output frequency. Version 3.1 now includes a graphical pre- and postprocessor for plotting/ visualization.

Limitations

Theoretical

For hydrodynamics and transport, the governing equations are laterally and layer averaged. Lateral averaging assumes lateral variations in velocities, temperatures, and constituents are negligible. This assumption may be inappropriate for large waterbodies exhibiting significant lateral variations in water quality. Whether this assumption is met is often a judgment call on the user and depends in large part on the questions being addressed. Eddy coefficients are used to model turbulence. Currently, the user must decide among several vertical turbulence schemes the one that is most appropriate for the type of waterbody being simulated. The equations are written in the conservative form using the Boussinesq and hydrostatic approximations. Since vertical momentum is not included, the model may give inaccurate results where there is significant vertical acceleration. Water quality interactions are, by necessity, simplified descriptions of an aquatic ecosystem that is extremely complex. Improvements will be made in the future as better means of describing the aquatic ecosystem in mathematical terms and time for incorporating the changes into the model become available in this one area. Many of the previous limitations have been addressed in the latest version. The following list describes the major assumptions in the water quality algorithms in the current version.

1. no zooplankton. The model does not explicitly include zooplankton and their effects on phytoplankton or recycling of nutrients.
2. no macrophytes. The model does not include the effects of macrophytes on hydrodynamics and water quality. In many cases, this is a good assumption.
3. simplistic sediment oxygen demand. The model does not have a sediment compartment that models kinetics in the sediment and at the sediment-water interface. This places a limitation on long-term predictive capabilities of the water quality portion of the model. If sediments are modeled, then the model is more predictive; however, sediment oxygen demand is still modeled in a simplistic manner.

Future releases will include the following additional capabilities:

1. any number of macrophyte groups and their affects on hydrodynamics and water quality
2. any number of zooplankton groups
3. sediment diagenesis algorithm that will compute SOD and sediment to water column nutrient fluxes based on organic matter delivery to the sediments
4. sediment transport including both cohesive and non-cohesive sediments
5. toxics
6. k-ε turbulence algorithm
7. simultaneous water surface elevation solution among all branches in a waterbody
8. downstream segment addition/subtraction between a river and a reservoir and/or estuary
9. Parallel version for use on multiprocessor machines

Summary

System-wide assessments for effective water resource management and evaluation of restoration activities are dependent upon realistic portrayals of the hydrology of the system and the response in material transport and transformation that affect the biological responses in the system. Our ability to realistically describe the hydrology and ecological responses of a system is often limited by resources (time, money, expertise), availability of appropriate data, and limitations of the various available tools. A web-based framework (as being developed in SMART) will provide planners access to a variety of tools that can be used by hydrologists and others associated with system-wide restoration activities within these limitations. Using tools such as the EFM for floodplain analysis for habitat response provides valuable connections between the hydrograph and biotic communities in the riparian/floodplain region. The ability to predict habitat type and success of restoration efforts at various locations in these regions is critical to the system-wide planning and implementation of restoration activities. Furthermore, detailed assessments of watershed and water body connections between physical, chemical, and biological responses are made possible with "combined approaches" such as HSPF coupled to CE-QUAL-W2. These approaches allow expansion of floodplain assessments to connect impacts in the upland (i.e., watershed) region and within the water resource (e.g., river, estuary). This connectivity greatly enhances the Corps mission to achieve environmental sustainability as described in the environmental operating principles.